(SU(2) Triplet)

Extended Higgs Sector from GUTs and EWSB

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The plan:

(i) motivation
(ii) extended Higgs sector from GUTs and SB
(iii) EW constraints
(iv) what is the triplet Higgs good for
(v) signatures
(vi) open questions

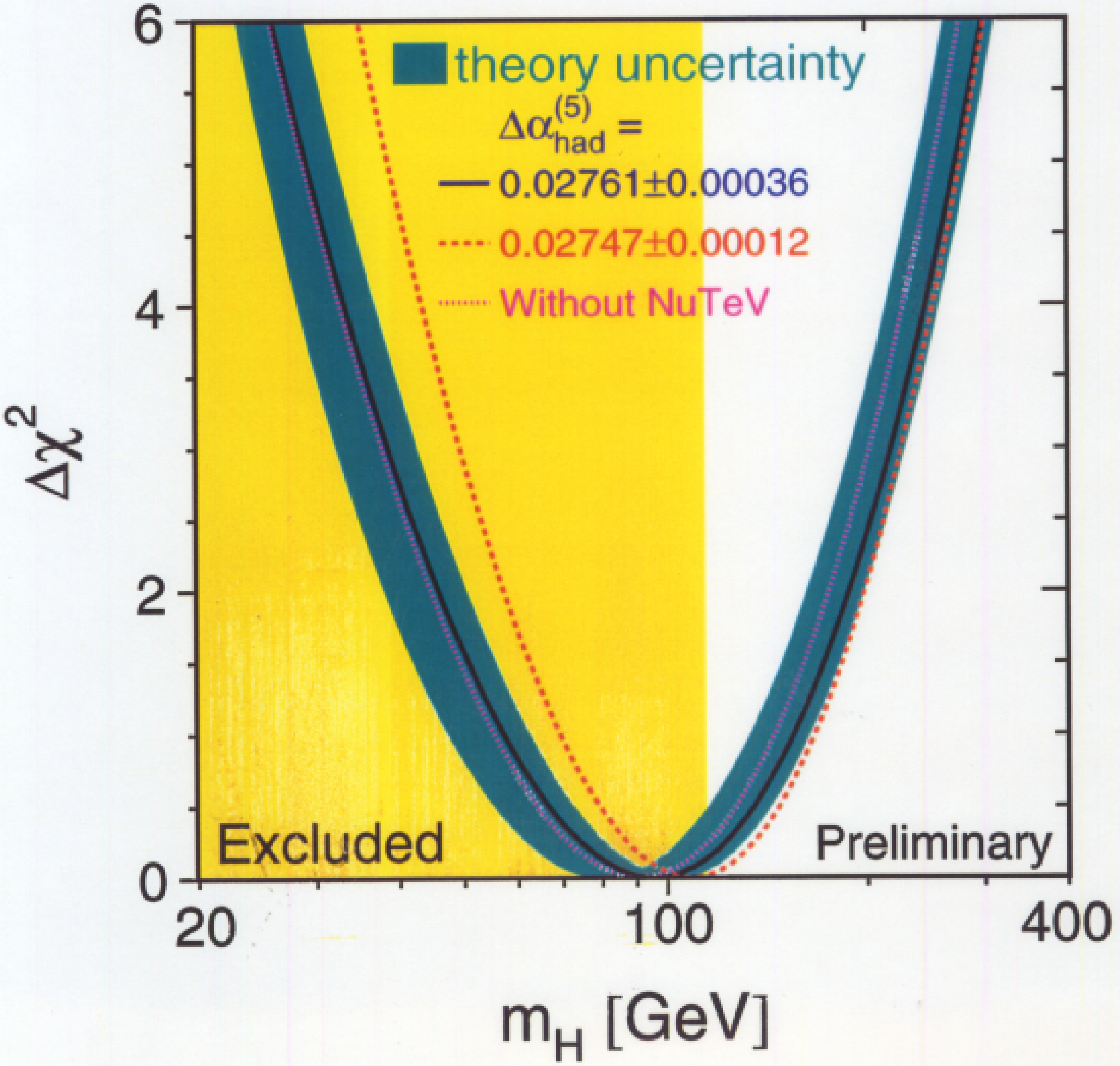
LEP
Summer 03

Some Hints from current data:

Global fit including all observables with

⇒ $m_H \simeq 96$ GeV is preferred ($81 \pm^{52}_{33}$ GeV)

⇒ lower than current limit from LEP: > 114 GeV



Why Extended Higgs Sector?

SM Higgs is predicted to be light, yet we have not found it!

There are several ways to evade the lower bound from LEP data: (Peskin and Wells, 2001)

$$\Delta T > 0, \quad \Delta S < 0$$

- Specific low energy effective models that have been looked at
  - $\Delta T > 0$
    - 2 Higgs doublets (Chankowski et al)
    - 4th generation (Dobrescu and Hill; He et al; ...)
  - $\Delta S < 0$
    - extra singlet Majorana fermions (Gates and Turning)
    - extra $SU(2) \times SU(2)$ multiplets (Dugan and Randall)
- extended scalar sector:
  - 4D GUT Models: lots of exotic scalars
  - GUTs in higher dimensions

    Orbifold boundary conditions can only break non-abelian symmetry: left over U(1)'s gauge symmetry breaking above EW scale $\Rightarrow$ by orbifold boundary conditions

EWSB $\Rightarrow$ by conventional Higgs mechanism; dynamical SB

$\Rightarrow$ much simpler Higgs sector compared to conventional 4D GUT models

– Little Higgs Models:

Higgs as a pseudo-Goldstone boson

Littlest Higgs Model: $SU(5)/SO(5)$

$$\mathbf{14} \to \underbrace{\mathbf{1}_0 \oplus \mathbf{3}_0}_{\text{eaten}} \oplus \underbrace{\mathbf{2}_{\pm 1/2}}_{\text{Little Higgs}} \oplus \underbrace{\mathbf{3}_{\pm 1}}_{\text{triplet}}$$

– Randall-Sundrum Model: Radion

Unification can also be achieved without SUSY by adding the following choices of Higgs representations $N_{T,Y}$ to the SM

(J. Gunion, hep-ph/0212150)

$N_{1/2,1}$	$N_{1/2,3}$	$N_{0,2}$	$N_{0,4}$	$N_{1,0}$	$N_{1,2}$	$\alpha_s(M_z)$	M_G (GeV)
1	0	0	2	0	0	0.106	4.0×10^{12}
1	0	4	0	0	1	0.112	7.7×10^{12}
1	0	0	0	0	2	0.120	1.6×10^{13}
2	0	0	0	1	0	0.116	1.7×10^{14}
2	0	2	0	0	2	0.116	4.9×10^{12}
2	1	0	0	0	2	0.112	1.7×10^{12}
3	0	0	0	0	1	0.105	1.2×10^{13}

⇒ lower unification scale compared to $M_{GUT} \sim 2 \times 10^{16} GeV$ in typical SUSY GUT scenario

⇒ proton decay NOT a problem, as there are NO X, Y gauge bosons, if not imbeded into a single gauge group (as in some string models)

Nontheless, no predictivity !!

Extended Higgs Structure from GUT Models

- Left-Right Symmetric Models: $\overset{W_L^{1,2,3}}{SU(2)_L} \times \overset{W_R^{1,2,3}}{SU(2)_R} \times U(1)_{B-L}$

  Typically $\quad Q_L \sim (2,0)\,, \quad Q_R \sim (0,2)$ $\quad\big|\; Q_{EM} = I_{3L} + I_{3R} + \frac{B-L}{2}$

  $\qquad\qquad\quad \ell_L \sim (2,0)\,, \quad \ell_R \sim (0,2)$

  $$1 \text{ bi-doublet } \quad \Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (2,2)$$

  $$2 \text{ complex triplets } \quad \Delta_L = \left(\Delta_L^{++}\Delta_L^{+}\Delta_L^{0}\right) \sim (3,1)$$

  $$\Delta_{L,R} = \begin{pmatrix} \Delta_{L,R}^{+}/\sqrt{2} & \Delta_{L,R}^{++} \\ \Delta_{L,R}^{0} & -\Delta_{L,R}^{+}/\sqrt{2} \end{pmatrix} \quad (Y=2) \qquad \Delta_R = \left(\Delta_R^{++}\Delta_R^{+}\Delta_R^{0}\right) \sim (1,3)$$

  – Symmetry breaking:

  $$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \overset{\langle\Delta_R\rangle}{\rightarrow} SU(2)_L \times U(1)_Y$$
  $$\overset{\langle\phi_1\rangle}{\rightarrow} U(1)_{ew}$$

  – Mass Spectrum:

  $\langle \Delta_R^0 \rangle \gg v_{EW}$, $M_{Z'}^2, M_{W_R}^2 \sim v_R^2 \rightarrow$ heavy

  $m_{\Delta_R} \sim m_{\Delta_L} \sim v_R$

  – Gauge coupling constant unification??

  require other matter fields at intermediate scale
  Lindner and Weiser, 1996

  need extra dimensions Perez-Lorenzana, Ponce, Zepeda, 1999; Perez-Lorenzana and Mohapatra, 1999

- $SO(10)$ Models:

  Minimal Higgs Sector ($G_{10} \to G_{2,2,4} \to G_{3,2,1}$)

$$\begin{aligned} 10 &= (1,1,6) + (2,2,1) \\ 16 &= (2,1,4) + (1,2,\overline{4}) \\ 45 &= (3,1,1) + (2,2,6) + (1,1,15) + (1,3,1) \\ 54 &= (1,1,1) + (2,2,6) + (1,1,20) + (3,3,1) \end{aligned}$$

  For Majorana masses of ν_R:

$$126 = (3,1,10) + (1,3,\overline{10}) + (2,2,15) + (1,1,\overline{6})$$

  Lots of exotic stuff!! They must be heavy, otherwise could lead to bad consequences, e.g. proton decay mediated by color triplet Higgsino (dim-5 operator) in SUSY SO(10) – "doublet-triplet splitting problem"

  (MS)SM Higgs doublet(s): linear combination(s) of SU(2) doublet components in 10, 16, and/or 126

The bottom line is:

Non-SUSY GUTs: can have light scalar fields in addition to the SM Higgs; nontheless predict low unification scale

SUSY GUTs: to preserve unification, require all but MSSM Higgs doublets heavy $\sim M_{GUT}$

From now on, concentrate on light Triplet Higgs and the Left-Right Symmetry Group

EW Precision Constraints

Oblique Corrections:

$$S = \frac{4s_w^2c_w^2}{M_z^2}(\Delta\Pi^{zz}(M_z) - \frac{c_w^2 - s_w^2}{s_w c_w}\Delta\Pi^{\gamma z}(M_z) - \Delta\Pi^{\gamma\gamma}(M_z))$$

$$T = \frac{1}{M_w^2}(\Pi^{ww}(0) - \Pi^{zz}(0)c_w^2)$$

$$U = 4s_w^2(\frac{\Delta\Pi^{ww}(M_w)}{M_w^2} - \frac{c_w}{s_w}\frac{\Delta\Pi^{\gamma z}(M_z)}{M_w^2} - \frac{\Delta\Pi^{\gamma\gamma}(M_z)}{M_z^2})$$

Very Model Dependent. Here are two examples:

- SM with a real SU(2) Triplet Higgs ($Y = 0$)
  (Blank and Hollik, 1998; Forshaw et al, 2001, 2003)

  The Lagrangian:

$$\mathcal{L} = |Dh|^2 + \frac{1}{2}|D\Delta|^2 - V_0(h, \Delta) \quad , \quad \Delta = \begin{pmatrix} \Delta^+ \\ \Delta^0 \\ \Delta^- \end{pmatrix}$$

  The scalar potential is

$$V_0 = \mu_1^2|h|^2 + \frac{\mu_2^2}{2}|\Delta|^2 + \lambda_1|h|^4 + \frac{\lambda_2}{2}|h|^2|\Delta|^2 + \lambda_3|\Delta|^4 + \lambda_4 h \Delta h^+$$

$\phi^0 \to z^0$

$$h = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}v + \phi_R^0 + i\phi_i^0 \end{pmatrix} \quad , \quad \langle\Delta\rangle = \begin{pmatrix} \eta^+ \\ \frac{1}{2}v\, t_\beta + \eta^0 \\ -\eta^- \end{pmatrix}$$

$g^\pm \to w^\pm$

$$\begin{pmatrix} g^\pm \\ h^\pm \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix}\begin{pmatrix} \phi^\pm \\ \eta^\pm \end{pmatrix} \quad , \quad \tan\beta = 2\frac{\langle\Delta\rangle}{\langle h\rangle}$$

$$\begin{pmatrix} H^0 \\ \Delta^0 \end{pmatrix} = \begin{pmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{pmatrix}\begin{pmatrix} h^0 \\ \eta^0 \end{pmatrix}$$

$m_h \simeq \lambda_1 v^2$

$m_{\Delta^0} \simeq m_{\Delta^\pm} \simeq \lambda_4 v^2/\beta$, $\beta \to 0$, custodial symm. restored

$\Delta m = m_{\Delta^0} - m_{\Delta^\pm} \simeq \beta^2 v$

at tree level:

$$M_W = \frac{g^2}{4}(v^2 + 4v_{1,0}^2), \quad M_Z = \frac{g^2 + g'^2}{4}v^2$$

Thus the model predicts

$$\rho^{\text{tree}} = 1 + \frac{4v_{1,0}^2}{v^2} = \frac{1}{cos^2\beta} > 1$$

$\beta =$ mixing angle between the charged components of the doublet and the triplet

at one-loop:

$$\begin{aligned}
\Delta S^{\text{tri}} &= 0, (Y = 0) \\
\Delta T^{\text{tri}} &= \frac{1}{8\pi^2}\frac{1}{s_w^2 c_w^2}[\frac{m_0^2 + m_c^2}{M_z^2} - \frac{2m_0^2 m_c^2}{M_z^2(m_0^2 - m_c^2)} ln(\frac{m_0^2}{m_c^2})] \\
&\sim \frac{1}{6\pi}\frac{1}{s_w^2 c_w^2}\frac{(\Delta m)^2}{M_z^2}
\end{aligned}$$

SM one-loop contributions:

$$\begin{aligned}
\rho^{\text{Higgs}} &= \frac{3}{16\pi^2}\frac{1}{s_w^2 c_w^2}[\frac{m_h^2}{M_z^2 - m_h^2} ln(\frac{m_h^2}{M_z^2}) - \frac{m_h^2 c_w^2}{M_z^2 c_w^2 - m_h^2} ln(\frac{m_h^2}{M_w^2})] \\
&\sim -ln(\frac{m_h^2}{M_w^2})
\end{aligned}$$

The effects of the triplet contributions > 1 (tree level)
$\Rightarrow$ making heavy SM Higgs possible! $\boxed{\beta \lesssim 4^\circ}$

For all EW precision observables: (Blank & Hollik)

Blank & Hollik

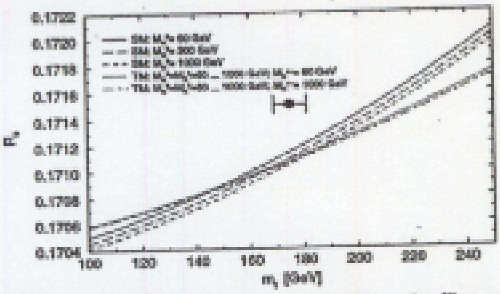
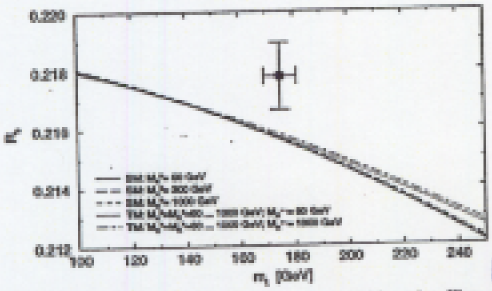


Figure 5.8: Top mass dependence of R_c in the SM and the TM for various Higgs masses. The error bar of R_c covers the full vertical axis.

R_b



m_t

Figure 5.9: Top mass dependence of R_b in the SM and the TM for various Higgs masses.

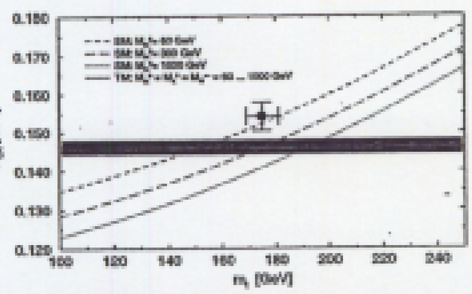


Figure 5.10: Left/Right asymmetry in the SM and the TM. The shaded area corresponds to a variation of $s_\ell^2 = 0.23165 \pm 0.00034$.

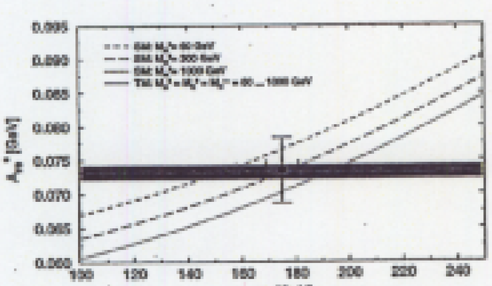
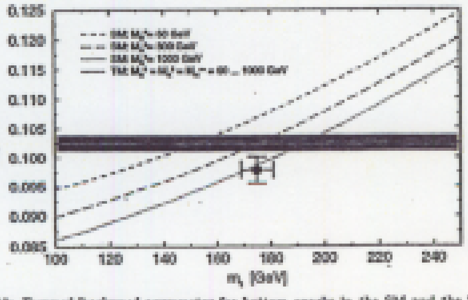


Figure 5.11: Forward/backward asymmetry for charm quarks in the SM and the TM. The shaded area corresponds to a variation of $s_\ell^2 = 0.23165 \pm 0.00034$.

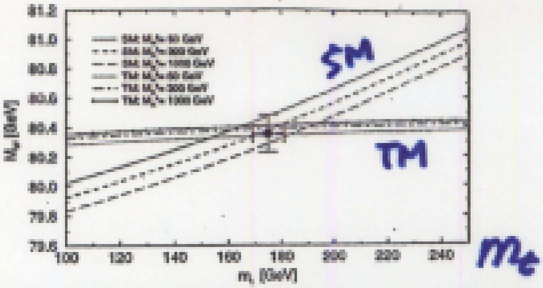
A^b_{FB}



m_t

Figure 5.12: Forward/backward asymmetry for bottom quarks in the SM and the TM. The shaded area corresponds to a variation of $s_\ell^2 = 0.23165 \pm 0.00034$.

M_W



m_t

Figure 5.1: Top mass dependence of M_W in the SM and the TM for various doublet Higgs masses M_{H^0}. The input values for the TM Higgs masses M_{K^0} and $M_{K^\pm}$ are 300 GeV.

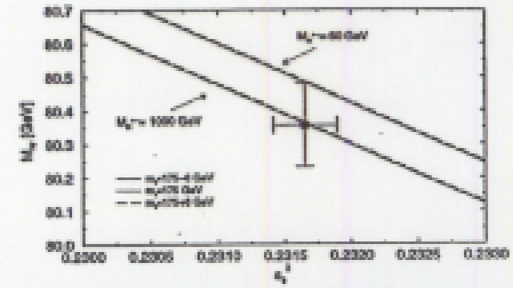
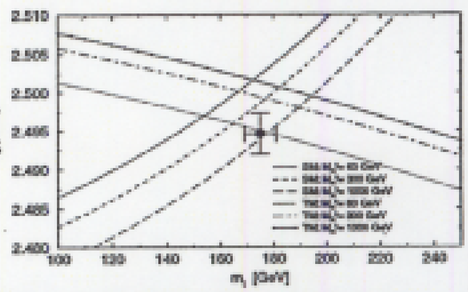


Figure 5.2: Dependence of M_W on the input parameter s_ℓ^2 for various values of m_t and M_{H^0} in the TM. The masses for the neutral Higgs bosons are fixed at 300 GeV.

Γ_Z



m_t

Figure 5.5: Top mass dependence of the total Z width in the SM and the TM for various doublet Higgs masses M_{H^0}. The input values for the TM Higgs masses M_{K^0} and $M_{K^\pm}$ are 300 GeV.

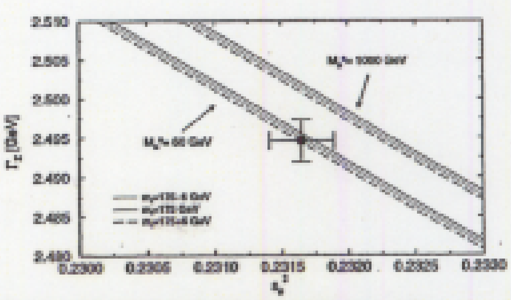


Figure 5.6: Dependence of the total Z width on the input parameter s_ℓ^2 for various values of m_t and M_{H^0}. The masses of the triplet Higgs bosons are fixed at 300 GeV.

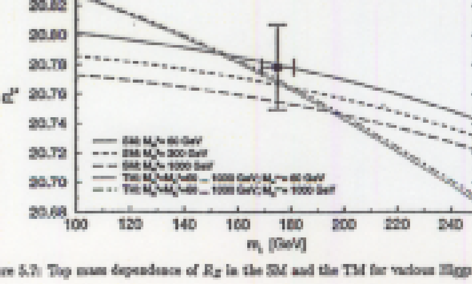


Figure 5.7: Top mass dependence of R_ℓ in the SM and the TM for various Higgs masses.

Predictions for all observables coincide with SM predictions, which fully agree with experiment except for R_b and A^b_{FB}:

Both models show similar deviation from data

Require quartic coupling constants for both SM Higgs and the triplet perturbative up to $\Lambda \sim 1 TeV$:

$$m_h < 520 GeV, \qquad (\lambda_1 |h|^4)$$
$$m_\Delta < 550 GeV, \quad (\tfrac{1}{2}\lambda_2 |h|^2 |\Delta|^2)$$

To pinpoint the mass of the SM Higgs via the indirect method: need to determine S independently of T better than ± 0.1 (Rosner, 2002)

- Left-Right Symmetric Model
  (Jegerlehner et al, 2000)

  $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

  model contains a complex SU(2) Triplet Higgses ($Y = 2$) and heavy gauge bosons, 1 bi-doublet

$$\langle \Delta_{L,R} \rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix}$$

$$\langle \Phi \rangle = \begin{pmatrix} k_1/\sqrt{2} & 0 \\ 0 & k_2/\sqrt{2} \end{pmatrix}, \quad \text{set } k_2 = 0$$

$$v_R \gg k_1 \sim v_{EW} \gg v_L \sim \frac{v_{EW}^2}{v_R}$$

at tree level: $< \Delta_L^0 >= v_{1,-1}$

$$M_W = \frac{g^2}{4}(v^2 + 2v_{1,-1}^2), \quad M_Z = \frac{g^2 + g'^2}{4}(v^2 + 4v_{1,-1}^2)$$

Thus the model predicts

$$\rho^{\text{tree}} = \frac{v^2 + 2v_{1,-1}^2}{v^2 + 4v_{1,-1}^2} < 1$$

at one loop:

Recall that in SM, top quark loop contribute to ρ parameter

$$\Delta\rho^{top} \simeq \frac{3\sqrt{2}G_F}{8\pi^2} m_t^2$$

In this model, this leading m_t^2 contribution is suppressed by heavy W_2 mass

$\Rightarrow$

$$\begin{aligned} \Delta r^{top} &= -\frac{c_w^2}{s_w^2}\Delta\rho \\ &= \frac{3\sqrt{2}G_F}{8\pi^2} c_w^2 \left(\frac{c_w^2}{s_w^2} - 1\right) \frac{M_{W_1}^2}{M_{W_2}^2 - M_{W_1}^2} m_t^2 \end{aligned}$$

For $M_{w_2} = 400 GeV$, the leading top quark contribution in this model is smaller than the $ln(m_t^2)$ contribution in SM!!

Prediction for top quark mass from oblique corrections is lost!!

Contribution from lightest Higgs: suppressed by heavy gauge boson masses:

$$\Delta r = \frac{\sqrt{2}G_F}{48\pi^2}\left(\frac{M_{w_1}^2}{M_{w_2}^2}\frac{c_w^2}{s_w^2}(1 - 2s_w^2) + \frac{M_{w_1}^2}{M_{z_2}^2}\frac{1}{s_w^2}(4c_w^2 - 1)\right)$$

$\Rightarrow$ model cannot be trivially ruled out!!

Unitarity Bound on Higgs Mass

Require Higgs self-coupling perturbative up to unification scale:

- With an additional gauge singlet:
  Tobe and Wells, 2002

  Non-SUSY case:

$$\begin{aligned} \sin^2\theta_w = 1/4 \quad &\Rightarrow \quad \Lambda = 3.8\,TeV,\ m_h < 460\,GeV \\ \sin^2\theta_w = 3/8 \quad &\Rightarrow \quad \Lambda \simeq 10^{13} GeV,\ m_h < 200 GeV \\ \Lambda = M_{pl} \quad &\Rightarrow \quad m_h < 180 Gev \end{aligned}$$

  SUSY case:

$$\begin{aligned} \sin^2\theta_w = 1/4 \quad &\Rightarrow \quad \Lambda = 37\,TeV,\ m_h < 350\,GeV \\ \sin^2\theta_w = 3/8 \quad &\Rightarrow \quad \Lambda \simeq 2 \times 10^{16} GeV,\ m_h < 120 GeV \end{aligned}$$

- MSSM with an additional triplet:
  Espinosa and Quiros, 1998

$$\Lambda \simeq 10^{17} GeV,\ m_h < 205\,GeV$$

- SM with an additional real triplet (Y=0):
  Forshaw et al, 2003

$$\Lambda \sim 1\,TeV,\ m_h < 520\,GeV$$

What is the SU(2) Triplet Higgs Good For?

- Neutrino Masses

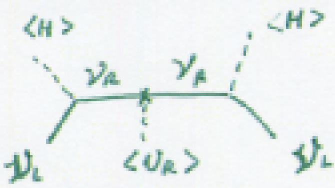
see-saw mechanism:

$$SO(10) \overset{v_{gut}}{\Rightarrow} SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\overset{v_R}{\Rightarrow} SU(2)_L \times U(1)_Y \Rightarrow \begin{pmatrix} 0 & 0 \\ 0 & f v_R \end{pmatrix}$$

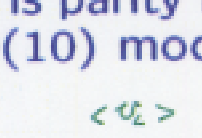
$$\overset{v_{ew}}{\Rightarrow} U(1)_{EW} \Rightarrow \begin{pmatrix} f v_L & h v_{ew} \\ h v_{ew} & f v_R \end{pmatrix}$$

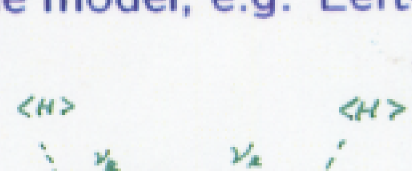
— Type I see-saw mechanism: without parity



$$\begin{pmatrix} 0 & M_{LR}^T \\ M_{LR} & M_{RR} \end{pmatrix}, \qquad M_\nu^{eff} = -M_{LR} M_{RR}^{-1} M_{LR}^T$$

— Type II see-saw mechanism: with parity
if there is parity in the model, e.g. Left-Right models, SO(10) models





$\langle v_L \rangle \neq 0$

$v_L \sim \frac{v_{EW}^2}{v_R}$

$$\begin{pmatrix} M_{LL} & M_{LR}^T \\ M_{LR} & M_{RR} \end{pmatrix}, \qquad M_\nu^{eff} = M_{LL} - M_{LR} M_{RR}^{-1} M_{LR}^T$$

$$f\,\frac{v_{EW}^2}{v_R} \quad - \quad \frac{v_{EW}^2}{f\, v_R}$$

parity symm.

- Bi-Large Mixing Angles
  - Family Symmetry: Type I see-saw mechanism
    Typically give hierarchical neutrino masses
    $m_{\nu_3} \gg m_{\nu_2} \gg m_{\nu_1}$
  - Renormalization Group Enhancement

    at GUT scale: starting with leptonic mixing matrix $= V_{CKM}$, nearly degenerate neutrino masses, and identical neutrino Majorana masses

    These boundary conditions can be satisfied, if

    $$\begin{aligned} M_{LL} \sim I \cdot v_L \quad &\Rightarrow \quad \text{degenerate masses} \\ M_{LR} M_{RR}^{-1} M_{LR} \quad &\Rightarrow \quad \text{mixing matrix} \sim V_{CKM} \end{aligned}$$

  - Minimal SO(10) Model with approximate $b-\tau$ unification

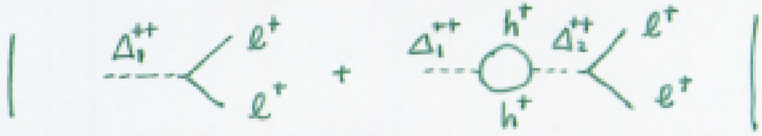
    both LH and RH Majorana mass terms for neutrinos have identical couplings (thanks to the parity)
    for small $\tan\beta$: atmospheric maximal mixing a consequence of $b-\tau$ unification

many natural scenarios require Typy II see-saw mechanism thus the SU(2) triplet Δ_L having non-zero VEV

(For a review on neutrino masses in SO(10) models, see e.g. M.-C. Chen and K.T. Mahanthappa, hep-ph/0305086)

- Leptogenesis through the decay of the triplet Higgs
  Ma and Sarkar, 1998

  First generate lepton Asymmetry: Interference between the CP violating decay of $\Delta^{++} \to l^+ l^+$ at tree level and one-loop:



  L is then converted to B due to EW anomaly

- Strong CP problem, SUSY CP problem:
  (Babu, Dutta, Mohapatra, Rasin, Senjanovic)

  SUSY Left-Right Model:

$$\overline{\Theta} = \Theta + \text{Arg det}(M_u M_d) - 3\text{Arg}(M_{\tilde{g}})$$

  Θ: coefficient of $F_{\mu\nu}\tilde{F}^{\mu\nu}$ term (P violating)

  P is invariant above scale $M_R \Rightarrow \Theta = 0$ above M_R

  Left-Right Symmetry $\Rightarrow$

$$m_{\tilde{g}} = \text{real above} M_R$$

Yukawa coupling constants hermitian

  $\overline{\Theta} = 0$ above M_R
  Below $M_R \Rightarrow$ RG corrections must be small so that $\overline{\Theta}$ is kept small

Signatures of the Triplet Higgs

(Gunion, Huitu, Maalampi, Pietila, Raidal, Cuypers, ...)

Tree level $H^{\pm}W^{\mp}Z$ vertex: generally present in models with triplet and/or higher Higgs representations

$Z \to H^{++}H^{--}$, $W^-W^- \to H^{--}$, current D0 bound $m_{\Delta^{--}} > 116$ GeV

- neutral sector
- singly charged sector
- doubly charged sector possible decay channels:

$$\begin{array}{lll} \Delta^{++} & \to & e^+e^+ \\ \Delta^{++} & \to & W^+W^+ \quad \text{suppressed as} < \Delta_L > \ll 1 \\ \Delta^{++} & \to & h^+W^+ \quad \text{suppressed by phase space} \end{array}$$

– Lepton number violation ($\Delta L = 2$) processes

$$f_{ij}L^T_{i,L}C\tau_2\Delta_L L_{j,L} =$$
$$f_{ij}(\underbrace{\Delta^0_L\nu_{i,L}\nu_{j,L}}_{\nu\text{- mass}} + \frac{1}{2}\Delta^+_L[\nu_{i,L}e_{j,L} + e_{i,L}\nu_{j,L}] + \Delta^{++}_{LL}e_{i,L}e_{j,L})$$

leads to $\Delta L = 2$ decay couplings

$$e^-e^- \to \Delta^{--}, \qquad \mu^-\mu^- \to \Delta^{--}$$

Currently we do not have any limit on $f_{\tau\tau}$

strongest constraints are for f_{ee} and $f_{\mu\mu}$: ($m_{\Delta^{--}}$ in GeV)

* from Bhabha scattering

$$|f_{ee}|^2 < 10^{-5} m_{\Delta^{--}}^2$$

* to avoid giving wrong sign contribution to $(g-2)_\mu$ deviation

$$|f_{\mu\mu}|^2 < 5 \times 10^{-7} m_{\Delta^{--}}^2$$

* from muonium-anti-muonium conversion:

$$|f_{ee} f_{\mu\mu}| < 10^{-7} m_{\Delta^{--}}^2$$

some weaker constraints:

* from $\mu^- \to e^- e^- e^+$

$$|f_{e\mu} f_{ee}| < 10^{-11} m_{\Delta^{--}}^2$$

If $< \Delta_L >= 0 \quad \Rightarrow \quad \Gamma^T_{\Delta^{--}}$ small
possibly very large s-channel e^-e^- and $\mu^-\mu^-$ production rates (Gunion, 1998)

can probe very small f_{ee}, $f_{\mu\mu}$ $\sim 10^{-16}$ at e^-e^- collider with $L = 300 fb^{-1}$

$\Rightarrow$ relevant range for see-saw
$\Rightarrow$ neutrino physics at the colliders